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# 120MM M830A1 HEAT ROUND WEAR LIFE PREDICTION

Sam Sopok

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ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
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# 120MM M830A1 HEAT ROUND WEAR LIFE PREDICTION


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## ABSTRACT

A wear life prediction is given for the US Army's M830A1 HEAT round used in the 120mm M256 and XM360 cannons. Five predictions are required and are provided for the fielding of the 120mm FCS MCS gun system. Four of these predictions are for the hot, basic ambient, cold, and severe cold round conditioning temperature cases. The fifth prediction is for the Fort Knox mixture of these four round conditioning temperatures known as the weighted averages per temperature for the computer correction factor. The peak one-meter long condemning wear band position is the 1.9 to 2.6 meter band centered at about 2.2 meter from the rear face of the tube for the M256 and the XM360 cannons. Cumulative equivalent M830A1 HEAT round wear-life predictions are given at the peak wear band positions for the selected round conditioning temperatures and the Fort Knox mix of these round conditioning temperatures. The M830A1 wear life predictions for the respective hot, basic ambient, cold, severe cold, and Fort Knox mixture of round conditioning temperature cases are 525, 750, 965, 1230, and 735 equivalent M830A1 rounds. Significant supporting data are provided to explain these wear-life predictions. Substantial firing data, non-destructive tube inspections, destructive tube characterizations calibrate the 120mm M830A1 computational modeling and resultant wear life predictions.


## INTRODUCTION

The US Army's Future Combat System Program is developing the 120mm XM360 gun system for its Mobile Combat System. The XM360's safe service wear life is required for the fielding of that gun system. A wear life determination is required for each 120mm round type. All wear life determinations already determined for the 120mm M256 gun system are directly applicable. A number of less erosive and new round types still require wear life determinations. This paper describes the wear life determination of the 120mm M830A1 HEAT round.

The 120mm M830A1 has a significantly longer wear life than the currently fielded M829A3 kinetic energy round. The M830A1 has not required a wear life determination since it has not caused a significant tube wear problem. Inspection reports and tube non-destructive inspections of a few dozen fired M256 tubes indicate that that the M830A1 round causes typical moderate tube wear to the M256 for each of the first, second, third, and fourth quarters of tube life. The center of the M830A1's wear band is about 2.2 meters from the rear face of the tube in the M256 and is about a meter long.

Substantial firing data, non-destructive tube inspections, and destructive tube characterizations calibrate the computational modeling that gives the 120mm M830A1 wear life predictions. The M830A1 associated firing data includes substantial pressure gage, muzzle velocity, and thermocouple measurements. The M830A1 associated destructive tube characterizations include macro- and micro-metallurgical and chemical characterizations of the worn and eroded bore areas of a few associated gun tubes. The firing of the M830A1 round causes typical wear due to degradation/erosion of the exposed gun steel interface through HC-chromium plate heat-check cracks. This results in HC-chromium platelet spalling and degradation/erosion of the fully exposed gun steel substrate.

## COMPUTATIONAL AND EXPERIMENTAL METHODS

The 120mm M830A1 wear life prediction draws upon a number of early computer models. In 1971, Levine [1] developed a transpiration and film cooling boundary layer model. It is a numerical solution of the turbulent boundary layer equations with equilibrium chemistry for rocket nose tip and nozzles.

Freedman [2] developed a non-ideal gas thermo-chemical equilibrium code for gun systems in 1982. In the 1980's, Dunn [3] developed a rocket nose tip and nozzle model for materials conduction, ablation, and erosion. Gough [4] developed a one-dimensional interior ballistic code for gun systems in 1990.

The basis of the 120mm M830A1 gun system wear-life prediction is a 1990's joint software development effort between U.S. Army Benet Labs and Software-and-Engineering-Associates (Carson City, NV). Dunn [5] developed a gun system model for mass addition cooling of a boundary layer that is a numerical solution of the turbulent boundary layer equations with chemistry in 1992. In that same year, Dunn [6] developed another gun system model for materials conduction, ablation, and erosion. In 1995, Dunn, Coats, Sopok, and others [7] developed their initial uncoated bore gun system wear and erosion life model. In 1996, Coats, Dunn and Sopok [8] developed a new gun system chemical equilibrium model with compressibility effects. In 2000, Sopok and Dunn [9] developed a coated bore gun system wear and erosion life model.

This joint development team continues to extend these models to this day. The basis for the M830A1 wear life prediction is computational modeling calibrated by substantial firing data, non-destructive tube inspections, and destructive tube characterizations.

The Figure 1 flow chart summarizes this jointly developed cannon coating wear and erosion model for the M830A1 wear life prediction. The codes are in solid bordered boxes, their associated inputs are in fine dashed bordered boxes, and their associated outputs are in a coarse dashed bordered box. This model predicts wall temperature profiles and thermal-chemical-mechanical wear and erosion profiles in bore coated cannons as a function of position, time, and round history.

This overall model is comprised of a number of interactively linked sub-models. These sub-models include the CCET thermo-chemistry cannon model, XNOVAKTC interior ballistics cannon model, MABL CFD boundary layer cannon model, MACE thermal cannon model, MACE wear and erosion cannon model, and BL cannon coating-substrate wear and erosion model.

Five M830A1 wear life predictions are required for and computed for the fielding of the 120mm XM360 gun system. These wear life predictions are equally applicable to the 120mm M256 gun system with its near identical internal geometry and interior ballistics. Four of these predictions are for the hot (49 C, 120 F), basic ambient (21 C, 70 F), cold (-7 C, 20F), and severe cold (-32 C, -25 F) round conditioning temperature cases. The fifth prediction is for the Fort Knox mixture of these four round conditioning temperatures known as the weighted averages per temperature for the CCF. This 120mm Fort Knox mixture includes 19% hot conditioned rounds, 64% basic ambient conditioned rounds, 16% cold conditioned rounds, and 1% severe cold conditioned rounds.

Computational modeling includes full-tube length predictions every 0.15 meters (6") for the surface wall temperatures, interface wall temperatures, stagnation wall temperatures, and their associated wear and erosion life predictions. Figures in this paper show data for eight selected axial positions including the 0.6 (24"), 1.5 (60"), 1.9 (72"), 2.1 (84"), 2.4 (96"), 2.6 (102"), 3.3 (133"), and 5.1 (204") meters from the rear face of the tube (RFT) positions for each of the four-selected round conditioning temperatures.

Typical 120mm tank gun bore HC-chromium plate thickness is nominally 0.13 mm (0.005"). The M830A1 round contains JA-2 propellant. Substantial gun system firing and tube inspection data calibrate these wear life predictions. Pressure gauge, radar, thermocouple, and kinetic rate data also calibrate these models. Nondestructive and destructive laboratory microscopic materials and chemical analyses of fired cannon specimens further calibrate these models. These analyses focus on substrate exposure, coating loss, cracks, pits, interfaces, voids, and surfaces. These include their crack/pit frequency, crack/pit width, coating platelet width, wall layers, residues, reactions, diffused species, and phase changes. These analyses are all as a function of position, time, and round history.

## RESULTS AND DISCUSSION

Computational 120mm M830A1 thermo-chemistry, interior-ballistics, CFD boundary layer, thermal, wear, and erosion predictions result in mean statistical output values. The CCET thermo-chemistry cannon model uses M830A1 configuration inputs (chemical, materials) to calculate gas-gas thermo-chemistry data for the interior ballistics, boundary layer, thermal, wear and erosion codes. Measured thermo-chemical data calibrates gas-gas product calculations.

The XNOVAKTC interior ballistics model computes the time-dependent core flow data for the boundary layer code using thermo-chemistry code output and gun system defining inputs. This gun system includes the 5.3-meter (17.3') 120mm M256 cannon, the similar interior ballistic/internal geometry 120mm XM360 cannon, the 120mm M830A1 JA-2 propellant, and other limited distribution projectile details. Measured pressure gauge and muzzle velocity data calibrate the time-dependent core flow calculation.

Figures 2-4 show the 120mm M830A1 XNOVAKTC interior ballistic model results. These figures respectively give maximum values of gas pressure (Pg), gas temperature (Tg), and gas velocity (Vg) as a function of selected axial positions at selected round conditioning temperatures. Maximum values, instead of time dependent values, compare round conditioning temperature cases.

These 120mm M830A1 interior ballistic results do not account for wall temperature effects by the burning combustible case, mass addition, wall phase changes, and gas-wall reactions. Gas pressure data is monotonically decreasing with travel. Similarly, gas temperature data is monotonically decreasing with travel. The gas velocity data is monotonically increasing with travel.

The 120mm M830A1 MABL computational fluid dynamic/boundary layer cannon model uses thermo-chemistry and interior ballistics model outputs to calculate boundary layer characteristics for the thermal and erosion models. Figures 5-6 show the MABL boundary layer model results for the 120mm M830A1 gun system. These figures respectively give maximum values of recovery enthalpy (Hr) and cold wall heat flux (Qcw) as a function of the selected axial positions at the selected round conditioning temperatures. Maximum values, instead of time dependent values, again compare round conditioning temperature cases. The MABL boundary layer model does account for wall temperature effects by the burning combustible case and mass addition.

In Figures 5-6, recovery enthalpy and cold wall heat flux both increase with increasing axial position to a peak 1.9-meter (72") to 2.6-meter (102") RFT band, then decrease thereafter to the muzzle. The MABL boundary layer cannon model calculates the bore heat flux every 0.15 meters (6") to determine the 1.9-meter to 2.6-meter RFT peak band position. This comprehensive MABL boundary layer analysis includes 1600 K combustible case gas cooling, mass addition, turbulent gas mixing, and turbulent gas heating effects. Figures 5-6 show these peak effects for recovery enthalpy and cold wall heat flux for the peak 1.9 meter to 2.6-meter RFT erosion band.

Figure 7 shows typical 120mm M830A1 round substrate exposure data as a function of axial position at selected percentages of equivalent M830A1 associated wear and erosion life. Steel substrate exposure includes cracks, pits and HC-chromium plate loss based on inspections of fired 120mm M830A1 gun system tubes. The center of the peak steel substrate exposure band is at approximately 2.2 meters RFT. The band is approximately one-meter in length.

Mean values of measured 120mm M830A1 cannon inspection and characterization data calibrates steel substrate exposure as a function of axial position at selected wear life percentages from a few dozen associated cannons. These selected erosion life percentages in Figure 7 are at 1% (nondestructively measured at post-proofing), 50% (exponentially estimated), 80% (exponentially estimated), and 100% (nondestructively and destructively measured at wear/erosion condemnation) of equivalent ambient conditioned M830A1 associated data.

Macroscopic and microscopic instrumentals measurements including those from a magnifying bore-scope, metallograph, scanning electron microscope calibrate substrate exposure. Nondestructive measurements verify that substrate exposure is approximately equal at the surface and interface.

Position dependent and equivalent wear/erosion life dependent substrate exposure measurements of fired cannons include axial and circumferential crack/pit frequency, crack/pit width, and platelet width. These measured substrate exposure patterns correlate with the boundary layer heat flux patterns that both increase with increasing axial position to the 1.9 to 2.6 meter RFT wear/erosion band peak then decrease thereafter to the muzzle.

This effort involves nondestructive inspections and in-wall thermocouple data from a few dozen 120mm M830A1 associated gun tubes. A few of these tubes were destructively characterized using macro- and micro- metallurgical and chemical methods. An extensive discussion of the theory and mechanisms of HC-chromium plated 120mm gun system wear and erosion is referenced[7-9]. These gun bore degradation, wear, and erosion mechanisms are fully applicable to the 120mm M830A1 gun system.

Figure 8 shows a typical normalized oxygen-induced gas-wall kinetic oxidation rate data for HC-chromium plate coating and steel substrate from one of a dozen associated 120mm M830A1 gas-wall degradation/kinetic rate studies. These data calibrate our 120mm M830A1 associated gas-wall thermo-chemistry model as a function of wall temperature, propellant chemistry, pressure, and time.

The CCET thermo-chemistry cannon model uses initial inputs (chemical, materials) to calculate gas-wall thermo-chemistry data for the thermal, wear, and erosion models. Measured 120mm M830A1 thermo-chemical data calibrate this model for gas-wall products and gas-wall reaction rates. Figure 9 gives CCET thermo-chemical model results for this 120mm M830A1 associated gun system. The figure gives simplified mean values for the reacting gas-wall enthalpy (Hgw) as a function of wall temperature (Twall) for the HC chromium plate coating and the steel substrate wall materials. Reacting gas-wall enthalpy values help calculate the thermo-chemical ablation potential (Ba). The CCET M830A1 thermo-chemical model does account for wall temperature effects by the burning combustible case, mass addition, wall phase changes, and gas-wall reactions.

Figure 10 shows typical 120mm M830A1 material degradation thresholds for HC-chromium plate coating and the gun steel substrate. These data calibrate our gas-wall thermo-chemistry model from destructive tube characterization, in-wall thermocouple, vented combustor study, and literature data. Surface and substrate degradation models of interfaces, cracks, pits and surfaces compute the area under a temperature-time curve above that particular degradation threshold. Calibrated diffusion controlled transformation codes evaluate multi-component steel system transformations.

The 120mm M830A1 round does not reach any of the HC-chromium plate thresholds in Figure 10. These unreached thresholds include the accelerated passivating oxidation by oxygen at about 2000 K forming $Cr_2O_3$, its transformation at about 2110 K, its melting point at about 2130 K, and its $Cr_2O_3$ melting point at about 2540 K.

The 120mm M830A1 round does reach some of the gun steel thresholds in Figure 10. These reached thresholds include its transformation onset at about 1000 K, its accelerated carbon diffusion at about 1050 K, its accelerated expansive-flaking scale-type oxidation onset by oxygen at about 1050 K forming FeO, its accelerated diffusion onset of carbon at about 1050 K forming $Fe_3C$, and its accelerated expansive-flaking scale-type oxidation onset by sulfur at about 1270 K forming FeS.

The 120mm M830A1 round does not reach some of the gun steel thresholds in Figure 10. These unreached thresholds include its melting point onset of its $Fe_3C$ white layer eutectoid at about 1420 K. its melting point onset of its FeS at about 1470 K, its melting point onset of its FeO at about 1640 K, its melting point onset at about 1700 K, and its melting point onset of its $Fe_3C$ at about 2110 K.

The 120mm M830A1 MACE coating-substrate thermal, wear, and erosion gun-system model use thermo-chemical model output, boundary layer model output, material properties input, firing history input, and firing scenario input to calculate wall temperature profiles and thermal-chemical-mechanical wall wear/erosion profiles. The model gives predicted results as a function of axial position, depth, time, and firing history, and firing scenario.

Experimental live-fire measured 120mm M830A1 input data destructively and nondestructively calibrate the associated thermal, thermo-chemical, wear, and erosion models. These data are from gas-wall kinetic rate functions, in-wall thermocouples, surface residues, subsurface residues in voids, and microscopic coating/substrate losses (crack, pit, interface, and surface wall materials). These data are also from thermal and chemical degradation of crack, pit, interface, and surface walls forming wall layers from reactions, diffusion, and phase changes. These gas-wall kinetic rate function data calibrate the thermo-chemical calculation and transform this chemical equilibrium calculation into a partial chemical kinetic calculation.

Figures 11-13 show 120mm M830A1 associated MACE gas-wall chemistry and adjusted thermal model results. These figures show the respective maximum wall temperature (Twall) results for the exposed HC chromium surface, unexposed steel interface, and the exposed steel surface (due to spalling of 0.13 mm thick chromium platelets) as a function of the selected axial positions at the selected round conditioning temperatures. Maximum values, instead of time dependent values, again compare round conditioning temperature cases. For each of these figures, the calculated maximum wall temperature patterns correlate with the boundary layer heat flux patterns in Figures 5-6 which increase with increasing axial position to 1.9 to 2.6 meter RFT peak band and decrease thereafter to the muzzle. The 120mm M830A1 MACE thermal, wear, and erosion model does account for wall temperature effects by the burning combustible case, mass addition, wall-phase changes, and gas-wall reactions.

Comprehensive 120mm M830A1 thermal and wear life modeling is conducted for the surface/interface wall temperatures and the stagnation wall temperature at the down-stream-side of the bore pits. Micro- metallurgical and chemical characterizations and thermocouple measurements calibrate the coating-substrate wear and erosion model. This calibration allows the prediction of resultant substrate interface temperatures for given crack and pit widths. This data includes the fully convective/exposed surface heating cases, the fully conductive/unexposed substrate interface heating case, and the substrate-exposure characterization data.

Figure 14 shows the 120mm M830A1 exposed substrate interface temperatures for given crack and pit widths versus travel for the hot 49 C (120 F) round conditioning temperature case. This figure shows maximum exposed interface temperatures instead of time dependent data as a function of HC chromium crack and pit width at selected axial positions for this 49 C round conditioning case. The basic ambient 21 C (70 F), cold -7 C (20F), and severe cold -32 C (-25 F) round conditioning temperature cases are determine similarly.

The 120mm M830A1 associated MACE model uses wall temperature data from Figures 11-14 to calculate corresponding surface and substrate interface wear and erosion rates. The MACE model calculates the substrate interface wear and erosion rates in cracks/pits as a function of exposure, position, time and rounds for the life of each crack and pit. The associated wear and erosion rate above each degradation threshold controls exposed steel interface degradation (transformation, reactions, etc) under a HC-chromium platelet. HC-chromium micro-pitting onset is due to HC-chromium platelet spalling allowing gas wash onset. The model adjusts for loss of interface contact.

This 120mm M830A1 method of calculating resultant substrate interface temperatures is calibrated based on measurements and characterizations conducted on these cannons that fired their most extreme rounds for a given crack or pit. Measured/characterized degradation includes steel substrate phase changes, chromium coating recrystallization and grain growth, steel substrate-combustion gas oxidation reactions, and steel substrate-combustion gas carburization reactions.

The existence and depth of the measured 120mm M830A1 degradations into the exposed steel substrate depends on and correlates with the magnitude of the associated position dependent wall temperature profiles. These measurements focus on the exposed steel substrate at the wall layers of cracks, pits, and interfaces as well as in-wall thermocouple data. Nondestructive characterization and destructive metallography/micro-chemistry characterizations of the peak erosion band positions calibrate interfacial micro-pitting onset temperatures.

The achievement of and magnitude above the 120mm M830A1 reaction thresholds are measured using in-wall thermocouples and nondestructive/destructive laboratory microscopic materials/chemical analyses of fired cannon specimens as a function of position, time and round history. Our bore coating erosion model requires measurable gas-wall coating and substrate reactivity data as a function of pressure, temperature and velocity. These data are from in-wall thermocouples and destructive characterizations of fired cannons, in-house measurements using specialized gas-wall kinetic rate testers, from the literature, and are dependent on gun system materials and configuration.

Figures 15-16 show cumulative erosion predictions for the 120mm M830A1 associated gun system. These include the respective values of cumulative rounds to initial 0.13 mm (0.005”) HC-chromium micro-pitting onset and initial 5 mm (0.197”) bore erosion condemnation onset as a function of the selected axial positions at selected round conditioning temperatures. The data in these two figures both inversely correlate with the above boundary layer heat flux and substrate exposure patterns. These wear and erosion life patterns versus travel start at bore onset, decrease to a 1.9 to 2.6 meter RFT minimum band, and then increased thereafter to the muzzle. HC-chromium plate loss at the muzzle is due to purely mechanical effects.

The 120mm M830A1 associated gun system has peak eroded and erosion-condemning bore damage significantly down-bore of the peak total heat transfer, peak bore heat affected zone depth, and peak bore radial crack depth that occurs at the bore onset positions. For the 120mm M830A1 associated gun system, peak bore wear and erosion occurs at the peak bore heat flux positions due to peak turbulent convective heating. This turbulent convective heating briefly raises exposed surfaces above irreversibly damaging and energy consuming degradation thresholds. These exposed surfaces are the bore surface and any exposed surfaces below the bore surface that the combustion gases can reach through cracks and pits. These exposed surfaces below the bore surface include the crack and pit wall surfaces and the worn/eroded exposed interfacial wall surfaces between the coating and substrate.

Figure 17 summarizes Figure 16 at the peak wear and erosion-condemning 1.9 to 2.6 meter RFT band positions for the 120mm M830A1 gun system. This peak worn/eroded band is centered on about 2.2 meters RFT and is about one meter in length. Figure 17 gives cumulative equivalent M830A1 associated rounds to wear and erosion condemnation at peak worn/eroded positions for the selected round conditioning temperatures and the Fort Knox mix of these round conditioning temperatures.

The respective hot, basic ambient, cold, severe cold, and Fort Knox mixture of round conditioning temperature cases have predicted 120mm M830A1 associated wear lives of approximately 525, 750, 965, 1230, and 735 equivalent M830A1 rounds at the peak-eroded band positions. The M830A1 round equally effects the 120mm M256 cannon and the similar interior ballistic/internal geometry 120mm XM360 cannon with a few exceptions. The XM360 does not have bore evacuator holes like the M256. The M256 does not have the XM360’s perforated muzzle brake. Substantial firing data, in-wall thermocouple measurements, non-destructive tube inspections, and destructive tube characterizations calibrate computational modeling and resultant 120mm M830A1 wear life predictions.

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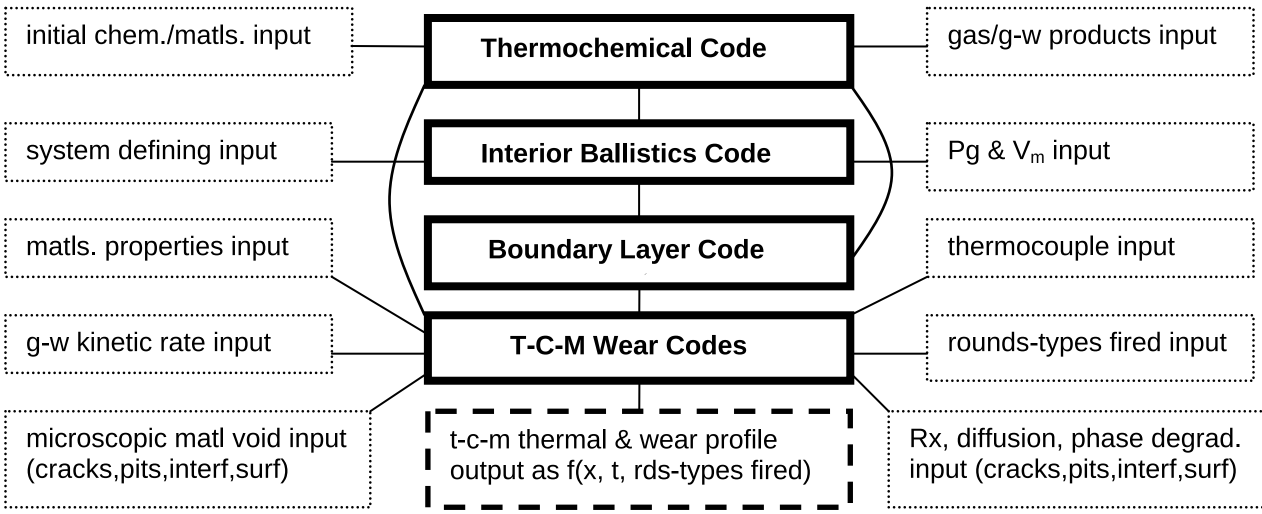



Figure 1 – Flow Chart of Cannon Coating Wear and Erosion Model

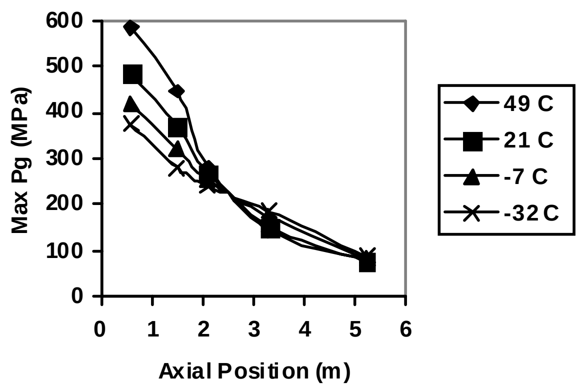



Figure 2- M830A1 XNOVAKTC Maximum Gas Pressure

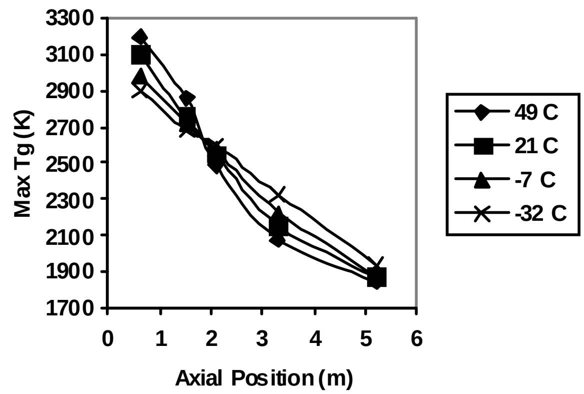



Figure 3 – M830A1 XNOVAKTC Maximum Gas Temperature

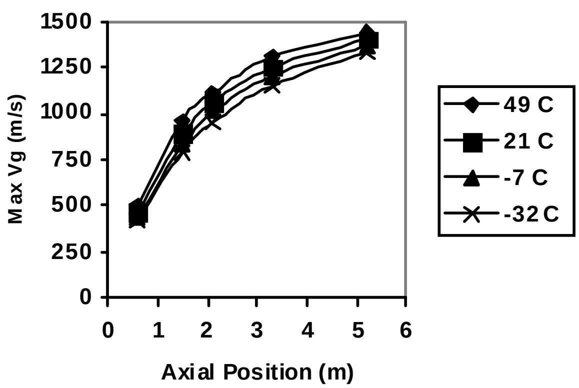



Figure 4 – M830A1 XNOVKTC Maximum Gas Velocity and Vm

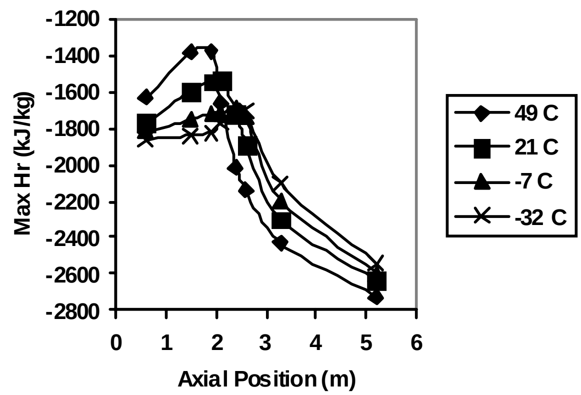
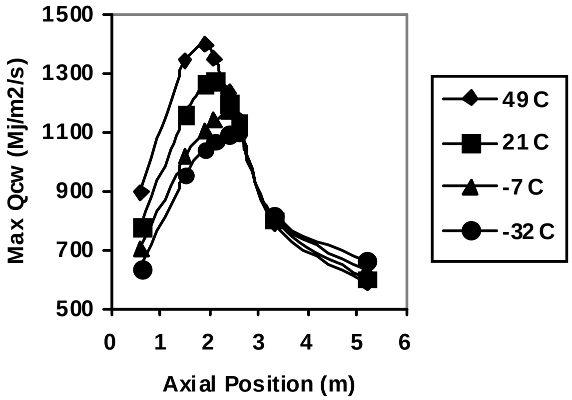



Figure 5 – M830A1 MABL Maximum Recovery Enthalpy



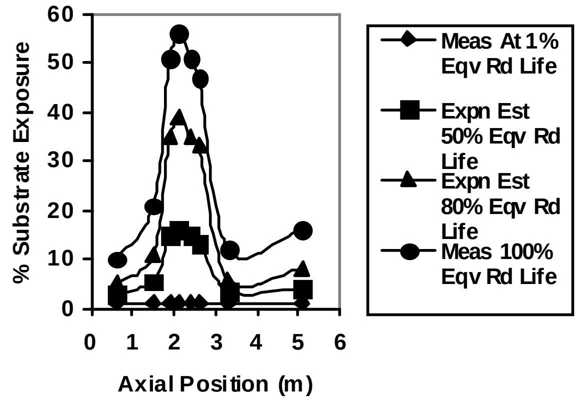
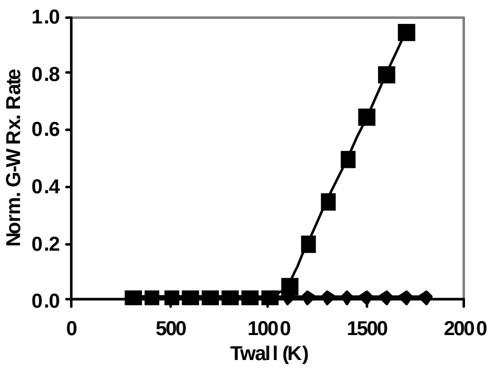




Figure 6 – M830A1 MABL Maximum Cold Wall Heat Flux

Figure 7 - Typical M830A1 Associated Substrate Exposure of Exposed Gun Steel



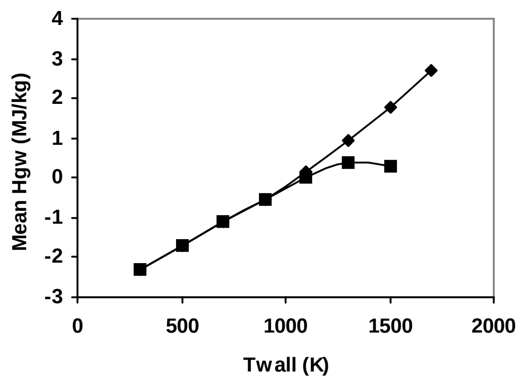
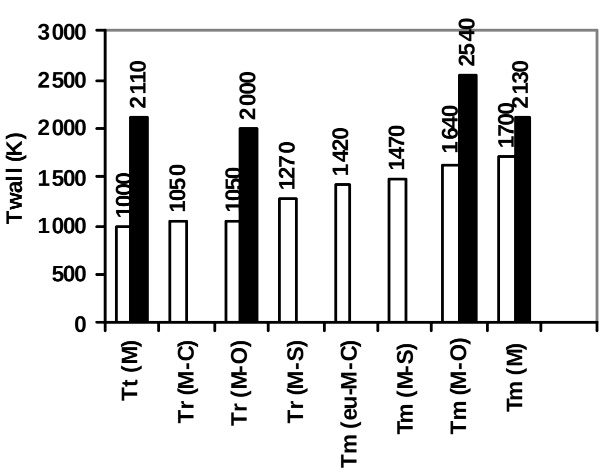




Figure 8 – M830A1 VC G-W Kinetic Oxidation Rate; Cr = Diamonds, Steel = Squares

Figure 9 – M830A1 CCET Mean G-W Enthalpy; Cr = Diamonds, Steel = Squares



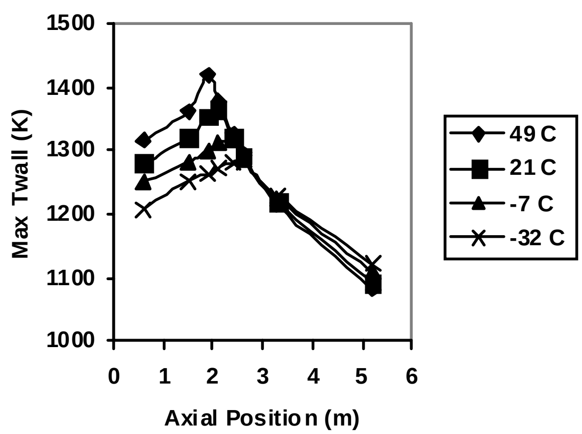




Fig 10 – M830A1 Mat'l Degradation Thresholds; HC-Cr = Black, Gun Steel = White

Figure 11 – M830A1 MACE HC-Cr Maximum Exposed Surface Temperature

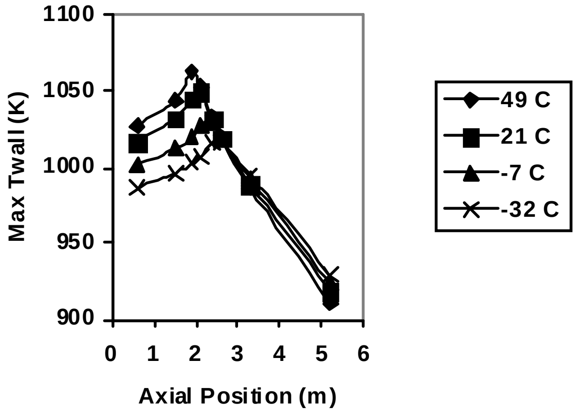



Figure 12 – M830A1 MACE A723
Maximum Unexposed Interface Temperature

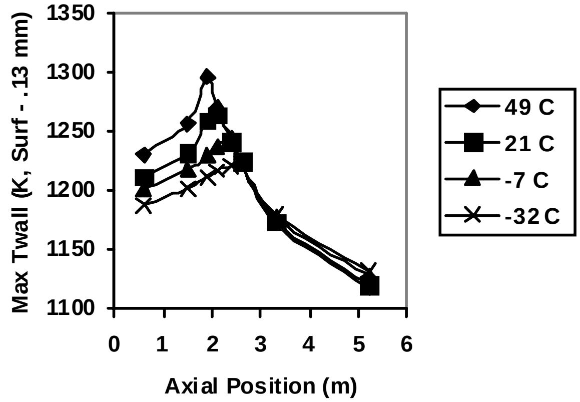



Figure 13 – M830A1 MACE A723
Maximum Fully Exposed Surface Temperature

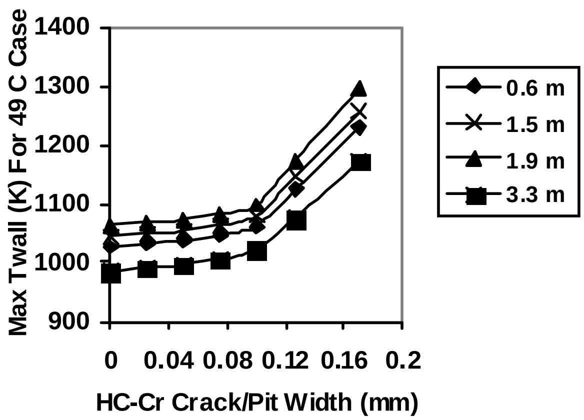



Figure 14 – M830A1 Maximum Exposed
A723 Temp at 49 C vs Crack/Pit Width

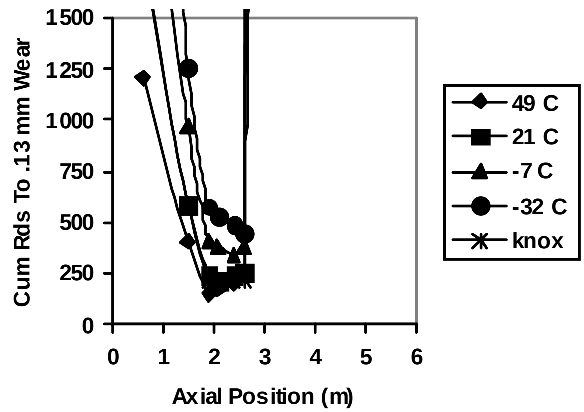



Figure 15 – M830A1 Micro-Pitting Onset
Due to 0.13 mm HC-Cr Loss by Position

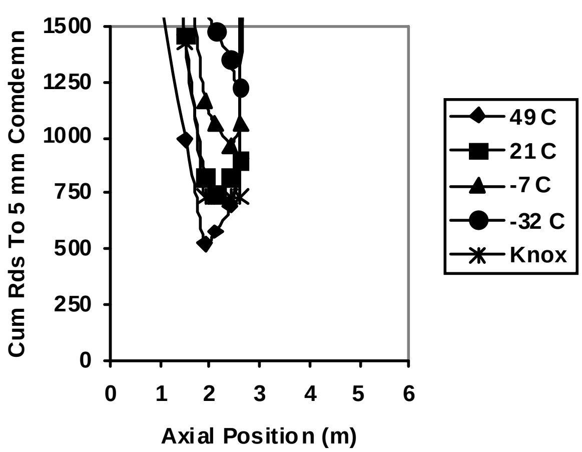



Figure 16- M830A1 Wear Condemnation
Due to 5 mm Pitting By Position

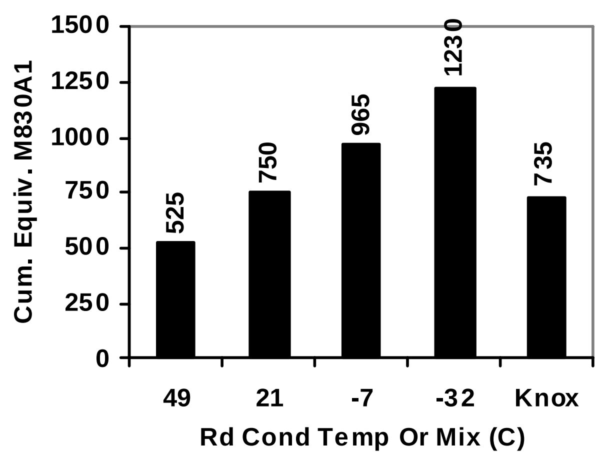



Figure 17 – M830A1 Peak Wear Summary for 1.9
to 2.6 m RFT Erosion Band